Article
Journal of Technology and Innovation
December 2022, Vol.9 No.25 1-7

Proposed algorithm for the design of planar inductors in implantable biomedical devices

Algoritmo propuesto para el diseño de inductores planos en dispositivos biomédicos implantables

SANTIAGO-AMAYA, Jorge†*, LÓPEZ-GARCÍA, C., AGUILAR-GUGGEMBUHL, Jarumi and SÁNCHEZ-DÍAZ, Francisco Xavier

Tecnológico de Estudios Superiores de Chalco, Carretera México Cuautla s/n, La Candelaria Tlapala, Chalco Estado de México. C.P. 56641, Mexico.

ID 1st Author: *Jorge, Santiago-Amaya* / **ORC ID:** 0000-0003-3432-4305, **CVU CONACYT ID:** 490214

ID 1st Co-author: *C., López-García* / **ORC ID:** 0000-0002-8361-8249, **CVU CONACYT ID:** 333862

ID 2nd Co-author: *Jarumi, Aguilar-Guggembuhl* / **ORC ID:** 0000-0001-5634-3086, **CVU CONACYT ID:** 69226-222733

ID 3rd Co-author: *Francisco Xavier, Sánchez-Díaz* / **ORC ID:** 0000-0001-7626-6524

DOI: 10.35429/JTI.2022.25.9.1.7 Received July 10, 2022; Accepted December 30, 2022

Abstract

This research deals with the development of an algorithm that calculates the characteristics of flat coils for implantable biomedical devices. This algorithm starts from the working frequency in which the inductors will be subjected to define the capacitive and inductive values, quality factor and bandwidth according to its geometry. Based on the calculations obtained by the proposed program, two tests were carried out, the first with two coils, one with an outer diameter of 10mm and the other with a 40mm diameter, the second test was with two coils of the same diameter. Where it is shown that the efficiency of the inductive coupling is subject to the distance between each coil. Notwithstanding to the fact that the operating frequency of the link and the characteristics of each inductor define its coupling factor and therefore the proportion of energy loss of its energy link.

Implantable, Biomedical, Subjected, Inductive, Proposed, Efficiency, Coupling, Development, Frequency, Proportion

Resumen

La presente investigación aborda el desarrollo de un algoritmo que calcula las características de bobinas planas para dispositivos biomédicos implantables. Este algoritmo parte de la frecuencia de trabajo en la que se someterán los inductores para definir los valores capacitivos, inductivos, factor de calidad y ancho de banda con forme a la geometría del mismo. Con base a los cálculos obtenidos por el programa propuesto, se realizaron dos pruebas, la primera con dos bobinas, una de 10mm de diámetro exterior y otro de 40mm, la segunda prueba fue con dos bobinas del mismo diámetro. Donde se demuestra que la eficiencia del acoplamiento inductivo este sujeto a la distancia entre cada bobina. Además de que la frecuencia de operación del enlace y las características de cada inductor definen su factor de acoplamiento y por ende la proporción de perdida de energía de su vínculo energético.

Implantable, Biomédico, Sujeto, Inductivo, Propuesto, Eficiencia, Acoplamiento, Desarrollo, Frecuencia, Proporción

Citation: SANTIAGO-AMAYA, Jorge, LÓPEZ-GARCÍA, C., AGUILAR-GUGGEMBUHL, Jarumi and SÁNCHEZ-DÍAZ, Francisco Xavier. Proposed algorithm for the design of planar inductors in implantable biomedical devices. Journal of Technology and Innovation. 2022. 9-25:1-7.

* Correspondence of the Author (Email: jorge_sa@tesch.edu.mx)
† Researcher contributing as first author.

Introduction

In recent decades, various researchers have developed different power systems that can power implantable biomedical devices (Fang, 2018), between these proposals, devices powered by batteries and magnetic induction (Fang, 2018), are defined. The first aspect is limited by the life of the battery, in addition to its extra size. The second implies the efficiency of the inductive link to energize said device and that decreases according to the distance between them (Harrison, 2007). However, the coupling by flat coils provides a more viable solution compared to devices that use batteries for their operation. The energization through the coupling of two coils is established by the principles of a transformer idea (Hernández-Sebastián et.al.,2020), where the coupling factor k is equal to 1. This value implies that all the energy radiated by the transmitting coil is equal to all the energy concentrated in the receiving coil (González, 2012). The value of k decreases as the link system presents coupling deficiencies between these (Robert L, 2017). This coupling is defined by equation 1.

$$k = \frac{M}{\sqrt{L_T * L_R}} \quad (1)$$

Where L_T is the inductance of the transmitting coil, L_R of the receiving coil and M the mutual inductance between them. Therefore, power transmission efficiencies are based on the inductance of each coil and the inductance between them. Zhao (2010), defines the calculation of the inductance of flat coils, based on four constants established by its geometry, see table 1, the vacuum permeability μ_0, its inner and outer diameter, equation 2.

$$L = \left[\frac{(\mu_0 N^2 D_{avg} C_1)}{2}\right]\left[\ln\left(\frac{C_2}{\rho}\right) + C_3\rho + C_4\rho^2\right] \quad (2)$$

Where ρ equals the filling ratio, D_{AVG} the average of the internal diameters D_{in} and external diameters D_{out}, these parameters are calculated by equations 3 and 4.

$$\rho = \frac{D_{out} - D_{in}}{D_{out} + D_{in}} \quad (3)$$

$$D_{AVG} = \frac{D_{in} + D_{out}}{2} \quad (4)$$

Geometry	C1	C2	C3	C4
Square	1.27	2.07	0.18	0.13
Hexagonal	1.09	2.23	0	0.17
Octagonal	1.07	2.29	0	0.19
Circular	1	2.46	0	0.2

Table 1 Coefficients to calculate the inductances of different coil geometries

However, a coil is made up of resistive and capacitive components as shown in figure 1. This in order to establish a resonance frequency to eliminate capacitive and inductive impedances in which the inductive link is established.

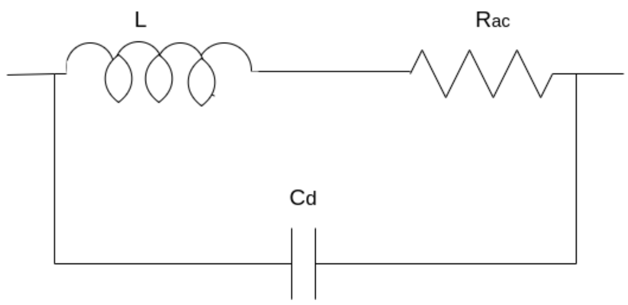

Figure 1 Equivalent circuit of a flat coil, L represents the inductance, R_{ac} resistive component and Cd the capacitance for the resonant circuit

The resistive component is made up of three types of resistance, direct current R_{DC}, skin effect δ and proximity R_p (Abbas, 2014) (Yousaf, 2013).

$$R_{ac} = R_{DC} + \delta + R_p \quad (5)$$

Where the Resistance R_{DC} is defined as the product of the resistivity coefficient of the material by its length, between its cross-sectional area, equation 6. The resistance due to skin effect is subject to the effects of the square root of the ratio between the resistivity of the material and the product of the frequency exerted by the permeability, equation 7. The proximity resistance originates when there is current in the two coils and that is capable of altering the magnetic flux between them (Mutashar, 2014) (Hernández-Sebastián, et. al., 2018). Where $w = f * 2\pi$, and f is equal to the oscillation frequency.

$$R_{DC} = \rho\frac{L}{S} \quad (6)$$

$$\delta = \sqrt{\frac{\rho}{\omega\mu_0}} \quad (7)$$

ISSN: 2410-3993
ECORFAN® All rights reserved.

The capacitive component is established according to the results obtained in the inductive and resistive calculations to determine the resonance frequency. Therefore, the total impedance of a flat coil is a function of its working frequency (Rendon-Nava, 2014) as shown in equation 8.

$$Z(w) = \frac{R_{ac}+jwL}{1-w^2LC_d+jwR_{ac}C_d} \quad (8)$$

$$Re(Z) = \frac{R_{ac}}{(1-w^2LC_d)^2+w^2(C_dR_{ac})^2} \quad (9)$$

$$Im(Z) = \frac{wL(1-w^2LC_d-\frac{C_dR_{ac}^2}{L})}{(1-w^2LC_d)^2+w^2(C_dR_{ac})^2} \quad (10)$$

This resonance frequency and its quality factor are characterized by equation 11 and 12, if ${R_{ac}^2}/{L^2} \ll {1}/{LC_d}$) equation 10 can be defined by equation 13.

$$W_{res} = \sqrt{\frac{1}{LC_d} - \frac{R_{ac}^2}{L^2}} \quad (11)$$

$$Q_0 = \frac{W_{res}}{\Delta w} \quad (12)$$

$$W_{res} = \frac{1}{\sqrt{L_0C_d}} * \sqrt{\frac{Q^2}{1+Q^2}} \quad (13)$$

Where Q_0 equals the quality factor, W_{res} angular resonance frequency and Δw bandwidth with a -3dB decay.

The calculation of the mutual inductance was defined by Reid R (Harrison, 2007). where it defines a method for prediction in the coupling of two planar coils related to each other, as shown in figure 2, where it describes the mutual inductance between the circumferences of the related coils, equation 13.

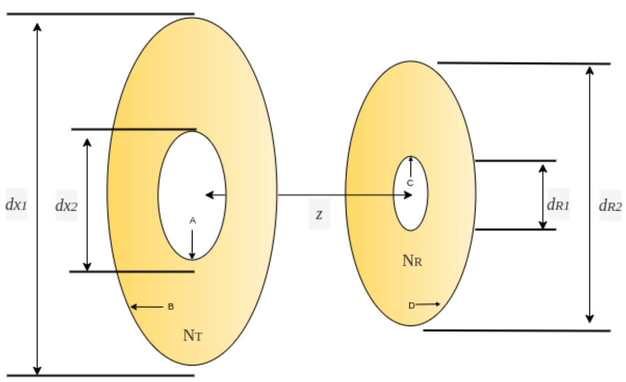

Figure 2 Coupling of two flat coils linked by magnetic fields

$$M = \frac{1}{2}\mu_0\sqrt{d_Td_R}\left[\left(\frac{2}{f} - f\right)K(f) - \frac{2}{f}E(f)\right] \quad (14)$$

Where M equals the mutual inductance, d_R and d_T diameter of the receiver and transmitter while f is the function that depends on the displacement z and the diameters of each coil, equation 14.

$$f(d_T, d_R, z) \equiv \sqrt{\frac{4d_Td_R}{(d_T+d_R)^2+z^2}} \quad (15)$$

The total inductance of the coil coupling is obtained by the average of the mutual inductances generated by the internal (A, D) and external (B, C) circumferences of each coil, as shown in equation 15. Where N_R es the number of turns of the receiving coil and N_T the number of turns of the transmitting coil.

$$M \approx N_TN_R\left[\frac{M_{AC}+M_{AD}+M_{BC}+M_{BD}}{4}\right] \quad (16)$$

Equations 1, 2, 8 and 13 establish that the position of the inductors, the oscillation frequency in which the coils work and their characteristics for implantable medical devices, mark the efficiency in energy transport. Where mutual inductance is a determining factor in energy transport and depends on the bond distance, as long as they are perfectly aligned with each other. For this reason, a visual studio program is proposed to calculate the characterization of flat coils for the design of implantable biomedical devices.

Methodology

As a first aspect, the algorithm calculates the inductance of the coil to be designed, for which the software asks the user for the geometry of the inductor, as shown in figure 3.

ISSN: 2410-3993
ECORFAN® All rights reserved.

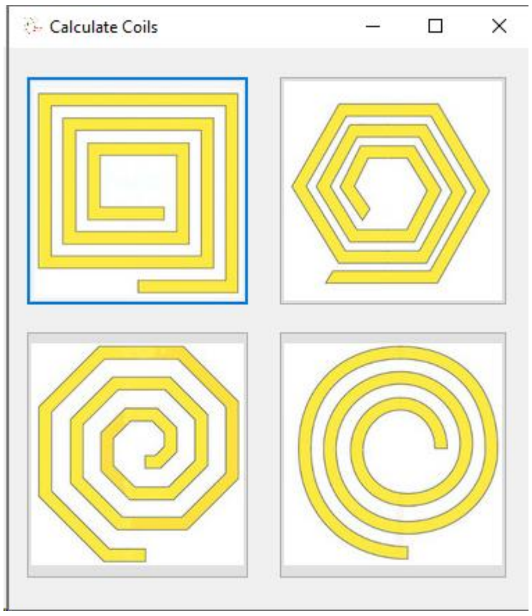

Figure 3 Graphical interface window to select the geometry of the coil to be designed

Once the geometry is defined, the program will again ask the user for the number of turns of the coil, the internal and external diameter, see figure 4, to calculate its inductance, this is done using equation 2.

Label	Description
a	Button to calculate inductance
b	Text box to enter the number of laps
c	Inside diameter
d	External diameter
e	Average diameters
f	Coil filling ratio
g	Text box to enter the relative permeability
h, i, j, k	Constants of the geometry of each coil
l	Vacuum permeability
m	Inductance

Table 2 Virtual control indicators in figure 4

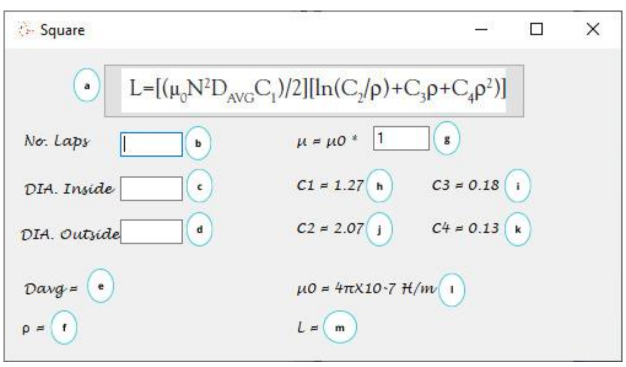

Figure 4 Interface to calculate the inductance of the coil, with respect to its geometry

With these data, the software will display the mean diameter, the filling ratio (ρ) and the inductance, figure 5. The calculation of the equivalent RLC circuit for the resonance frequency of the inductor is managed by the RC button, and it will only be activated if the user enters, the width, thickness and material of the inductor track, notwithstanding to the working frequency and the medium of propagation.

Label	Description
a	coil inductance
b	Inside diameter
c	coil resistance
d	Work Frequency
e	track width
f	track thickness
g	Material
h	other material
i	coil turns
j	coil perimeter
k	Capacitance
l	Vacuum permeability
m	Button to calculate the RLC circuit
n	propagation medium
o	Other means of propagation

Table 3 Virtual control indicators in figure 5

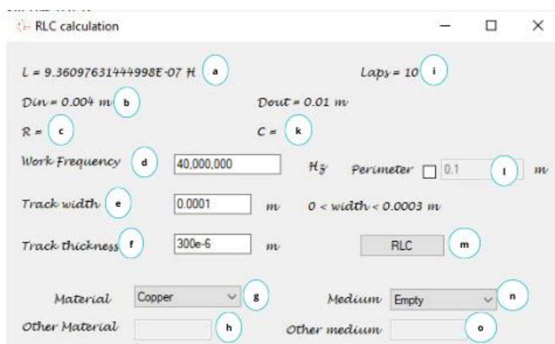

Figure 5 Interface for calculating the RLC equivalent circuit of the inductor

The width of the track is used to find the resistance of the coil, which is related to the thickness of the track, the material that makes it up and the medium in which it propagates. The results of the equivalent circuit of the calculated coil are generated through an interface that shows the equivalent circuit and its frequency response, figure 6.

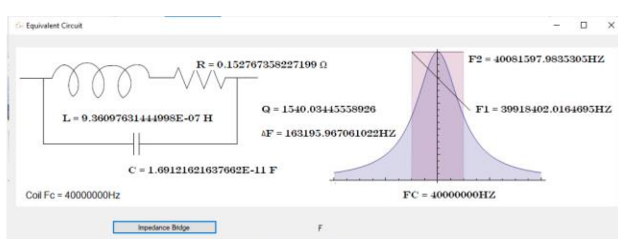

Figure 6 Interface window of the RLC equivalent circuit and the bandwidth of the coil, as well as its quality factor

ECORFAN® All rights reserved.

The evaluation of the software was carried out with a base resonance frequency of 40 Mhz for two flat coils, the first with an external diameter of 10 mm and 4 mm in its internal diameter "coil A". The results are observed in table 3 where the inductance, resistance and capacitance are shown together with the coupling factor of each geometry of the calculated coil.

	L	R	C	Q
Octagonal	0.805μH	0.0845 Ω	19.6pF	2393.60
Circular	0.784μH	0.079 Ω	20.01pF	2465.53
Square	0.936μH	0.101 Ω	16.91pF	23101.33
Hexagonal	0.8056μH	0.088 Ω	19.66pF	2295.63

Table 3 Results of the program for the design of a flat coil of 10 mm width

In the second coil, it was calculated with a diameter of 10 mm internal radius and 40 mm external radius "coil B". The characterization of the geometries of each coil is shown in Table 4.

	L	R	C	Q
Octagonal	0.395μH	0.015 Ω	40pF	6474.30
Circular	0.392μH	0.0145 Ω	40.3pF	6792.38
Square	0.4685μH	0.0184 Ω	33.79pF	6373.72
Hexagonal	0.3902μH	0.016 Ω	40.57pF	6129.9

Table 4 Results of the program for the design of a 40 mm wide flat coil

The calculations obtained show that the circular coil has a lower resistance than the other coils, which gives it a better-quality factor. However, for practical design purposes in the manufacture of the inductors, only square coils and a 40 Mhz oscillator with an amplitude of 8V at a current of 50 mA were built, as shown in figure 7.

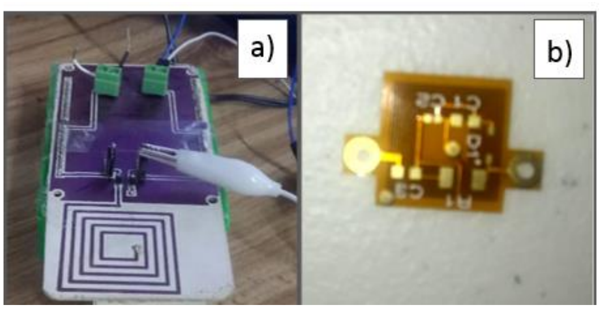

Figure 7 a) 40 MHz oscillator module and 40 mm transmitter coil b) 10 mm receiver coil

Results

Two tests were performed at distances between 0 and 7 cm, figure 8, the first test was with a coil A and B, according to the characteristics calculated by the software. The values of the voltage measurements of the first test are observed in table 5 and its behavior of this voltage in figure 9. While the results of the second test are observed in table 6 and figure 10.

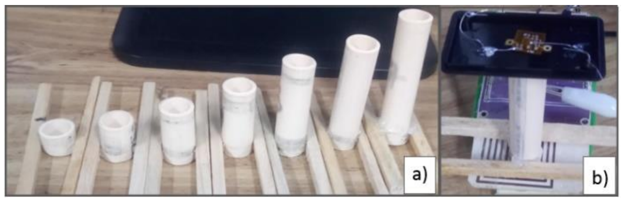

Figure 8 a) Cylinders for measuring the adsorption of the receiving antenna. b) placement of each cylinder between the two antennas

Distance (cm)	Voltage (mV)	Efficiency (%)
0	300	3.75
1	80	1
2	20	0.25
3	6	0.075
4	20	0.25
5	18	0.225
6	17	0.2125
7	9	0.1125

Table 5 Efficiency test results of the receiving antenna (10 mm)

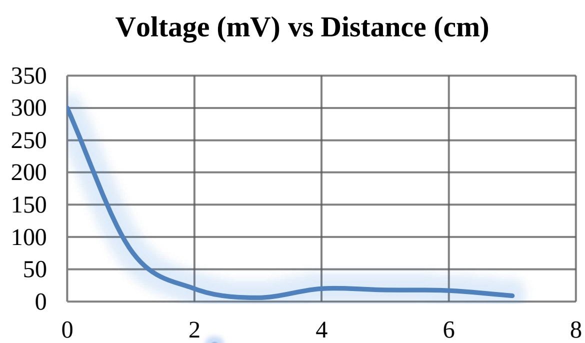

Figure 9 Graph of the voltage obtained with respect to the distance of table 4

Distance (cm)	Voltage (mV)	Efficiency (%)
0	2000	25
1	640	8
2	290	3,625
3	135	1,6875
4	75	0,9375
5	52	0,65
6	44	0,55
7	34	0,425

Table 6 Efficiency test results of the receiving antenna (40 mm)

ISSN: 2410-3993
ECORFAN® All rights reserved.

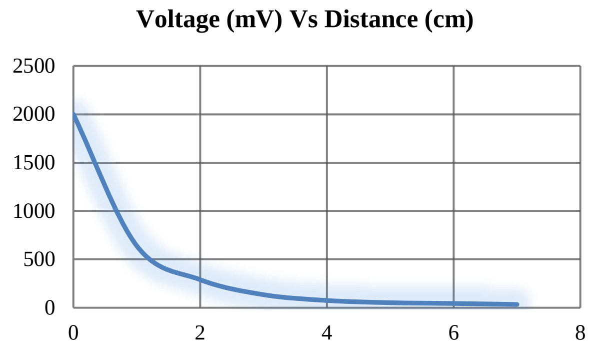

Figure 10 Graph of the voltage obtained with respect to the distance of table 5

Nevertheless, measurements were made of two coils of 40 mm external diameter that were coupled together at a distance of 1.5 cm apart, the results in voltage and efficiency are shown in table 7 and figure 11.

Frequency MHz	Voltage (mV)	Efficiency (%)
40	400	5
16	40	0,5
12	30	0,375
6	20	0,25
4	10	0,125

Table 7 Transmission efficiency results with respect to frequency

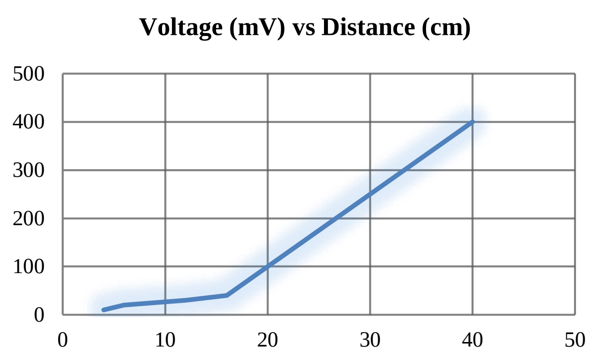

Figure 11 Graph of transmission efficiency with respect to frequency

Thanks

Tecnológico de Estudios Superiores de Chalco
SYS-DT S.A de C.V

Conclusions

The size of the coupled flat coils is a determining factor in the efficiency of the inductive link, nevertheless to the quality factor of each of them, since it governs the amount of radiation or absorption.

It is deduced by equation 13 described by Reid R (Harrison, 2007) and confirmed by the graphs in figures 10 and 11. This efficiency is also determined by the coupling distance between them and the working frequency radiated by the transmitting coil (Hernández-Sebastián et.al., 2018 and Hernández-Sebastián et.al., 2020), this is due to the fact that, if the inductive link does not oscillate at the resonant frequency of the inductors, capacitive and inductive impedances are generated that prevent the passage of current in both, as can be seen in the graph in figure 6.

References

Abbas, S. M., Hannan, M. A., Samad, S. A., & Hussain, A. (2014). Inductive coupling links for lowest misalignment effects in transcutaneous implanted devices. Biomedical Engineering/Biomedizinische Technik, 59(3), 257-268. ISBN: 978-0-12-374127-1

Fang Y, Hou W, Zhou W, Zhang H. [Advances in Implantable Medical Device Battery]. Zhongguo Yi Liao Qi Xie Za Zhi. 2018 Jul 30;42(4):272-275. Chinese. doi: 10.3969/j.issn.1671-7104.2018.04.012. PMID: 30112893.

González E. Á. (2012). Osciladores clase E de alta eficiencia. Tesis de grado. Escuela Técnica Superior de Ingenieros Industriales y de Telecomunicación. Universidad de Cantalabria.

Harrison, R. R. (2007, May). Designing efficient inductive power links for implantable devices. In 2007 IEEE International Symposium on Circuits and Systems (pp. 2080-2083). IEEE. Doi: 10.1109/ISCAS.2007.378508

Robert L. Boylestad. Person DecimoTercera Edicción (2017). Introducción al Análisis de Circuitos. ISBN: 970-26-0448-6

Hernández-Sebastián, N., Díaz-Alonso, D., Renero-Carrillo, F. J., Villa-Villaseñor, N., & Calleja-Arriaga, W. (2018). Design and simulation of an integrated wireless capacitive sensors array for measuring ventricular pressure. Sensors, 18(9), 2781. Doi:10.3390/s18092781

ECORFAN® All rights reserved.

December 2022, Vol.9 No.25 1-7

Hernández-Sebastián, N., Villa Villasenor, N., Renero-Carrillo, F. J., Diaz Alonso, D., & Calleja Arriaga, W. (2020). Design of a fully integrated inductive coupling system: a discrete approach towards sensing ventricular pressure. Sensors, 20(5), 1525. DOI: 10.3390/s20051525

Mutashar, S., Hannan, M. A., Samad, S. A., & Hussain, A. (2014). Analysis and optimization of spiral circular inductive coupling link for bio-implanted applications on air and within human tissue. Sensors, 14(7), 11522-11541. Doi: 10.3390/s140711522

Rendon-Nava, A. E., Díaz-Méndez, J. A., Nino-de-Rivera, L., Calleja-Arriaga, W., Gil-Carrasco, F., & Díaz-Alonso, D. (2014). Study of the effect of distance and misalignment between magnetically coupled coils for wireless power transfer in intraocular pressure measurement. The Scientific World Journal, 2014. Doi: 10.1155/2014/692434

Yousaf, A., Boccard, J. M., Khan, F. A. and Reindl. L. M. (2013), Journal of Sensors and Sensor Systems. Near-field wireless sensing of single and multiple. Doi:10.5194/jsss-2-35-2013

Zhao, J. (2010). A new calculation for designing multilayer planar spiral inductors; A new simple and accurate expression lets you calculate the coupling factor between multilayer PCB inductors. Pulse-EDN. Doi:10.5194/jsss-2-35-2013.

ECORFAN® All rights reserved.